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PROCESS-BASED MODELLING OF WAVE INDUCED SALT MARSH EDGE EROSION

MICHELE BENDONI[1], HOCINE OUMERACI[2], DANO ROELVINK[3]

[1] *Department of Civil and Environmental Engineering, University of Florence, Florence, Italy,*
mbendoni@dicea.unifi.it

[2] *Leichtweiß-Institut for Hydraulic Engineering and Water Resources, TU-Braunschweig, Braunschweig, Germany,*
h.oumeraci@tu-bs.de

[3] *UNESCO-IHE, Water Science and Engineering Department, Delft, Netherlands,*
d.roelvink@unesco-ihe.org

ABSTRACT

A process-based model for the lateral retreat of a cross-shore transect of salt marsh under wave attack is developed. Several modifications are implemented in the widely used numerical model XBeach: i) the processes involving the mutual interaction between sand and mud; ii) the effect of halophytic vegetation on modifying the near flow field and in increasing the critical shear stress for soil erosion, and iii) the effect of partially reflected waves on the steep profile of the marsh scarp. Furthermore, the bed elevation update algorithm is modified in order to resemble the lateral retreat of the scarp. Numerical simulations of a salt marsh edge subject to continuous wave forcing are run to investigate the effect of different processes and parameters (e.g. soil composition and vegetation characteristics) on the evolution of the system. Preliminary results show a significant dependence of the marsh scarp behaviour on the relative sand-mud composition. The effect of vegetation in mitigating erosive processes nonlinearly decreases when the relative mud fraction is reduced. The model provides important insights into the processes associated with salt marsh edge erosion.

Keywords: salt marsh, waves, erosion, numerical model

1. INTRODUCTION

Salt marsh edge erosion is one of the main processes responsible for the reduction of salt marsh areas in several parts of the world (Marani et al., 2011; Mariotti and Fagherazzi, 2010). Studies based on field measurements revealed a relation between erosion rates and wave energy flux (e.g. Schwimmer, 2001; Marani et al., 2011). Laboratory experiments provided a qualitative description of the retreat process (Francalanci et al., 2013) or focused on specific failure mechanisms (Bendoni et al., 2014). Numerical studies attempted to simulate the lateral retreat of the salt marsh edges interacting with the morphology of the surrounding environment at the basin scale (Mariotti and Fagherazzi, 2013), either for long term forecast (Mariotti and Fagherazzi, 2010) or focusing on the longitudinal (2D) evolution of the marsh boundaries (Leonardi and Fagherazzi, 2014). Despite these diverse studies, the influence of the local characteristics of the salt marsh bank on its evolution is still not sufficiently understood. A more detailed description of the effect of waves on marsh edge erosion and related morphodynamic processes is needed, particularly in numerical modelling.

In this study, a process-based 1D hydro-morphodynamic model is presented. For this purpose, the existing model XBeach (Roelvink et al., 2009)is used as a numerical framework in which several modifications are implemented. The modifications are reported and discussed in the next section. Tentative simulation results using the modified XBeach model are then shown. Finally, concluding remarks are drawn, also including implications for further developments of the model.

2. MODIFICATIONS TO THE NUMERICAL MODEL XBEACH

The main framework of the numerical model XBeach remains unchanged and the aforementioned modifications are added as new subroutines. In Figure 1, a sketch of the model structure is depicted.

The interaction of sand p_s [-] and mud p_m [-] fractions (p_m+p_s=1) is implemented following the approach proposed by Van Ledden (2003). Sand-mud mixtures behave cohesively (C) or non-cohesively (NC) depending on whether p_m is higher or lower than of a critical mud fraction $p_{m,cr}$. The erosion parameters, relating the characteristics of the hydrodynamic forcing to the erosion rate [$m^3/m^2/s$], are affected by the relative fraction of mud p_m, in both in cohesive and non-cohesive regimes. The same holds for the critical shear stresses $\tau_{cr,C}$ and $\tau_{cr,NC}$ [N/m^2] in the cohesive and non-cohesive regime, resepctively. Moreover, during sediment settling it is assumed sand and mud do not interact.

The effect of wave reflection is included through a reflection coefficient K_r [-], determined from the local morphology and incident wave parameters. The average slope of the scarp is approximated by a linear regression of z_{bi} (bed elevation of i-th cell) on x_i (spatial coordinate of i-th cell), considering the cells within one wave length from the waterline. It is assumed that the effect of the reflected wave height H_R decreases exponentially backward from the waterline. The reflected waves with height H_R are considered to influence the quantities directly involved in the morphodynamic evolution of the system such as the bottom orbital velocity (increased), the wave momentum having an effect on the mean flow (decreased) and the Stokes Drift (decreased).

Following the approach by Mendez and Losada (2004), vegetation affects the short wave energy balance with parameters specifically referred to salt marsh plants such as drag coefficient, stem width and density. Critical shear stress for soil erosion is increased by the presence of vegetation using a modified version of the relation proposed by Tuan and Oumeraci (2012) for sea dikes.

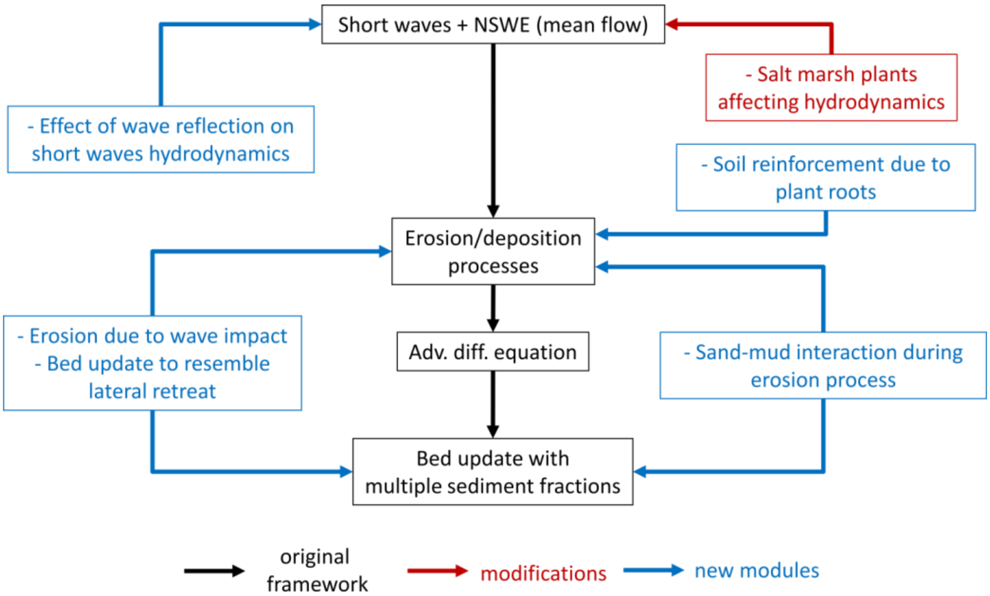

Figure 1. Sketch representing the interaction among processes in the model. Black text represent the main original XBeach framework, light blue text the processes included in new subroutines and red text the modified subroutines (NSWE, Non Linear Shallow Water Equation).

The erosion rate of the scarp e_{sc} [m^2/s] is linearly proportional to the incident wave energy flux $P = E \cdot n \cdot c_p$ [W/m] through an erodibility parameter, where $E = 1/8\rho g(H_{rms})^2$ [J/m^2], $n = ½[1+2k \cdot h/\cosh(k \cdot h)]$ [-] and $c_p = \omega/k$ [m/s]. k [m^{-1}] and ω [s^{-1}] are respectively the wave number and wave period and h [m] is the water depth. The cells part of the scarp have a slope (determined in an upwind manner) exceeding a threshold value, set equal to 0.15. In order to emphasize the local effect of waves, it is assumed that the erosion rate e_{sc} is not distributed uniformly along the scarp. This means different parts of the bank tends to erode horizontally at different rates E_{sc} [m/s] (Figure 2a,b), which can be considered as the “recession rate” of the scarp. E_{sc} is determined so that:

$$e_{sc} = \int_{z_{b,toe}}^{z_{b,top}} E_{sc} dz_b \qquad [1]$$

where $z_{b,toe}$ and $z_{b,top}$ are the elevation of the toe and the top of the bank scarp. The update of the bed due to wave impact within $z_{b,toe}$ and $z_{b,top}$ is expressed by:

$$\frac{\partial z_b}{\partial t} + \frac{f_{mor}}{1-n_p} E_{sc}(h, z_b) \frac{\partial z_b}{\partial x} = 0 \qquad [2]$$

where f_{mor} is the morphological acceleration factor (Roelvink, 2006) and n_p is the bed porosity. When the erosion process due to wave impact is activated the avalanching mechanism is deactivated (Roelvink et al., 2009).

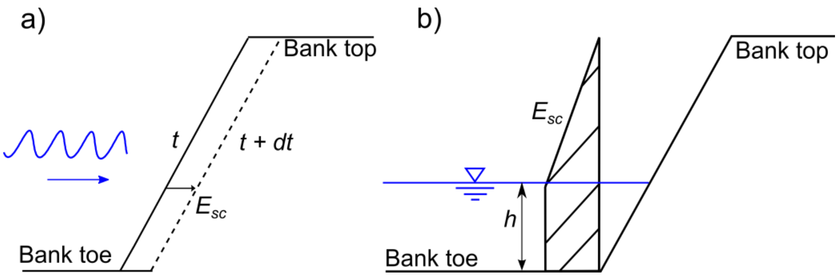

Figure 2. Principle sketches of a) the lateral retreat process where (E_{sc} = celerity at which scarp translates horizontally due to wave impact); b) the vertical distribution of the celerity E_{sc} along the scarp.

3. PRELIMINARY RESULTS

Simulations are run for different bank compositions by varying the proportions of p_m and p_s respectively in the ranges 0.9-0.4 and 0.1-0.6. The comparison of the final scarp profiles allows one to estimate to which extent the evolution of the system is influenced by the characteristics of the soil matrix. Furthermore, numerical simulations in presence of vegetation are run considering two different bank compositions (p_m = 0.8, p_s = 0.2 and p_m = 0.4, p_s = 0.6) in order to investigate the effect of slat marsh plants on the final profiles. For each simulation, the bank has been subject to continuous wave forcing modulated by the tide (Figure 3a). The following values of the main parameters are used: H_{rms} = 25 cm, Tp = 2 s, $\Delta h_{tide} \approx 1$ m, T_{tide} = 12 hours, f_{mor} = 10, duration = 6 days. Critical mud content $p_{m,cr}$ is set to 0.3 as suggested by Van Ledden

(2003). In Figure 3b the results for four different proportions of p_m and p_s are reported. It appears that the mud content strongly influences the erosion trend of the bank and for $p_m > 0.75$, the system seems to be not affected by the increasing mud fraction. The effect of vegetation is more pronounced at lower mud fractions (Figure 3d), whereas for higher mud fractions the final scarp profiles with and without vegetation almost overlap.

4. CONCLUSIONS

A 1D hydro-morphodynamic model for the simulation of the wave induced erosion of the salt marsh edge is developed within the XBeach model. The model is employed to analyse the effect of different bank features, such as soil composition and presence of vegetation, on the evolution of the morphology of the marsh scarp. Results show that an initial scarp profile, characterized by a step-like shape, tends to evolve towards a more gentle profile with decreasing mud fraction. The presence of vegetation decreases the intensity of the erosive process. The effect is more pronounced for lower mud fractions and decreases for higher mud fractions.

At this stage mass failure events are implicitly accounted in the global erosion rate of the scarp induced by wave impacts. Next step will consider the effect of mass failures and the presence of slumped blocks at the bank toe in modifying the behaviour of the system. The effect of vegetation will be further investigated considering different plant typologies and distributions.

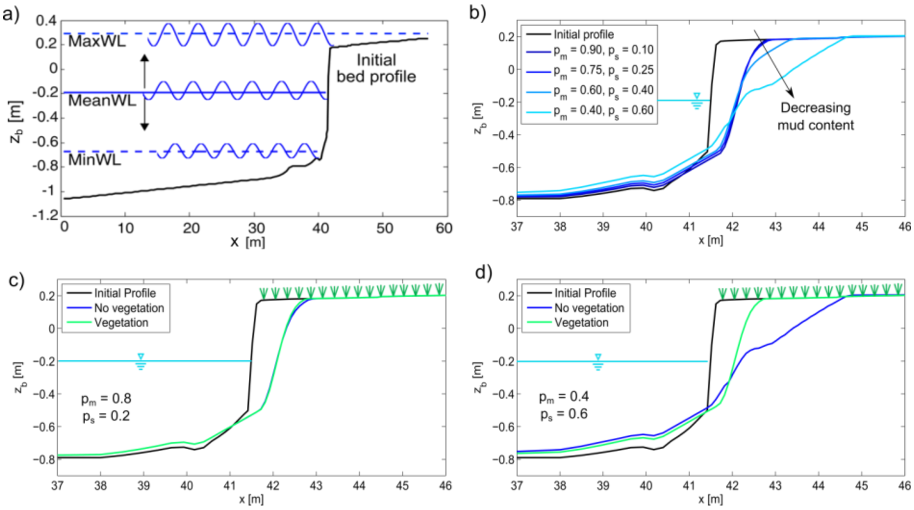

Figure 3. a) Initial bank profile and tidal wave amplitude (1 m) employed for the simulations. b) Comparison of final scarp profiles for four different simulations varying the composition of the bank soil. Black line represents the initial profile. Lines from dark to light blue representing the final profile with decreasing mud content. c) Comparison of final profiles in case vegetation is considered (green line) or not (blue line) for $p_m = 0.8$ and $p_s = 0.2$. d) Comparison of final profiles in case vegetation is considered (green line) or not (blue line) for $p_m = 0.4$ and $p_s = 0.6$.

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